SuperPower Inc.

superior performance.
powerful technology.

Development, Manufacturing and Applications of 2G HTS Wire at SuperPower

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Center for Emergent Superconductivity - Fall 2011 Workshop
University of Illinois, Urbana, IL, November 8-9, 2011

Outline

- About SuperPower
- 2G HTS wire applications and market
- Device development & demonstration
- 2G HTS wire architecture & manufacturing approach
- Manufacturing to meet demanding market
- Wire development
- Summary

SuperPower Inc.

SuperPower – focus on 2G HTS wire technology

- Formed in 2000 to develop 2G HTS technology for energy applications
- Subsidiary of Royal Philips Electronics since 2006 acquisition of Intermagnetics General Corp.
- Headquarters and manufacturing operation in Schenectady, NY
- R&D group in Houston, TX
- ~65 employees
  - Highly skilled workforce
  - Recognized experts from around the world

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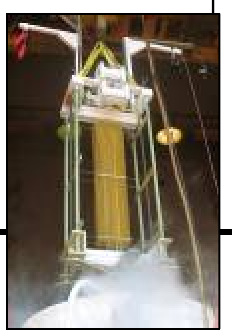
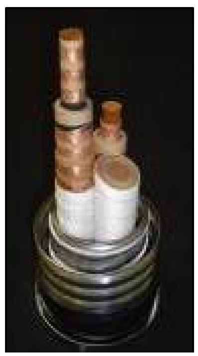
HTS device portfolio - What are the winning devices?

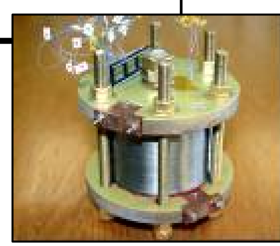
Energy	Defense	Transportation	Industrial	Medical	Science/ Research
• **Cable** • **FCL** • **Generators** • **Transformers, incl. FCL** • **Storage** – **SMES** – Flywheels	• **Motors** • **Cables** • Directed energy weapons	• **Maglev** • Motors • Rail engines	• **Induction heaters** • **Motors** • **Generators** • Magnetic separation • Bearings	• **Current leads** • **MRI** • NMR	• **HF magnets** • **Space exploration** • SQUIDS • High energy physics • Electronics • Cell tower base station filters



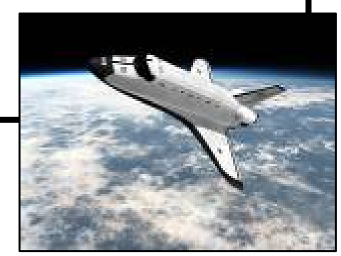


Courtesy of SuperPower and Sumiktomo

Courtesy of Waukesha



Courtesy of Oswald



Key:

- **Near-Term addressable: 1-5 years**
- **Mid-Term: 3-7 years**
- **Longer term: 5-10 years**

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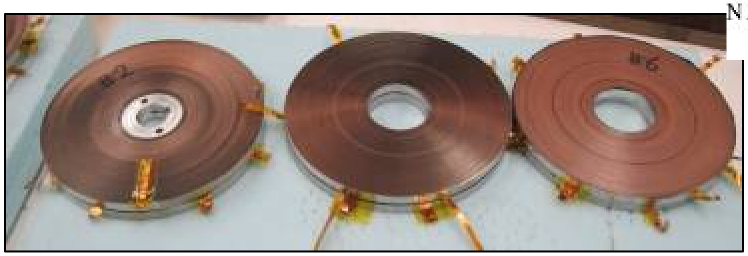
Demanding coil applications for 2G HTS wire

3.6 T gantry magnet for **Particle Beam Therapy**. Four racetrack coils and 14 bent coils. 2,500 m with min I_c of 115 A/4 mm.

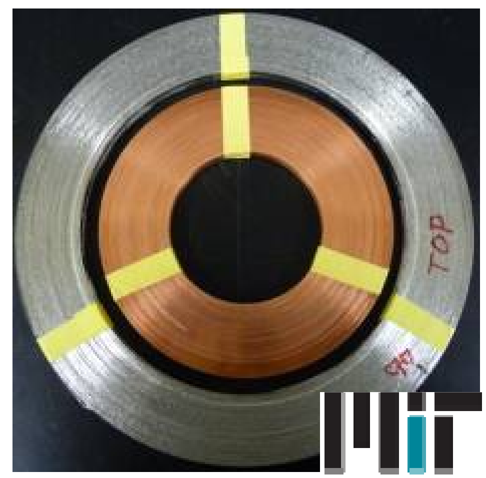
Linear Induction Motor using 3 mm wide conductor to reduce ac losses

Race track coils for **generator**

BROOKHAVEN
NATIONAL LABORATORY



20+T HTS **solenoid for muon collider**

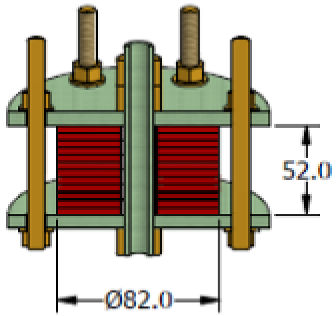


Massachusetts Institute of Technology

1.3 GHz NMR Magnet
8.34 T contribution from coated conductor coil

Ultra high-field magnets demonstrated at 4.2 K with AP wire

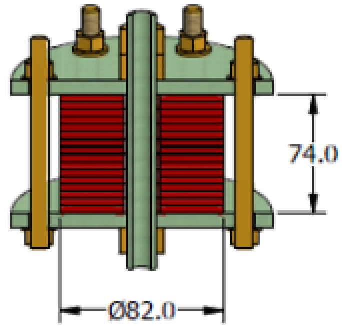
- J_e ~ 300 A/mm^2
- Stress levels 300 – 400 MPa



SuperPower I.

Bmax = 26.8 T

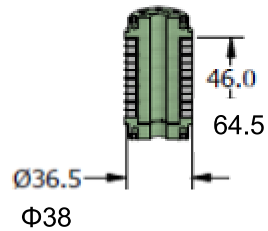
ΔB = 7.8 T



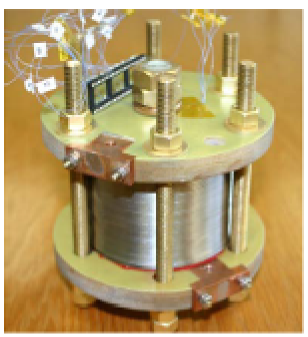
SuperPower II.

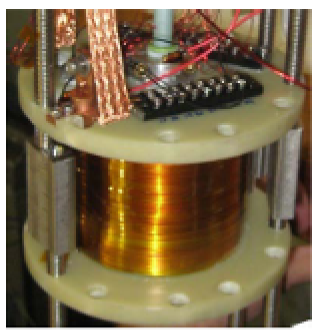
Bmax = 27 T

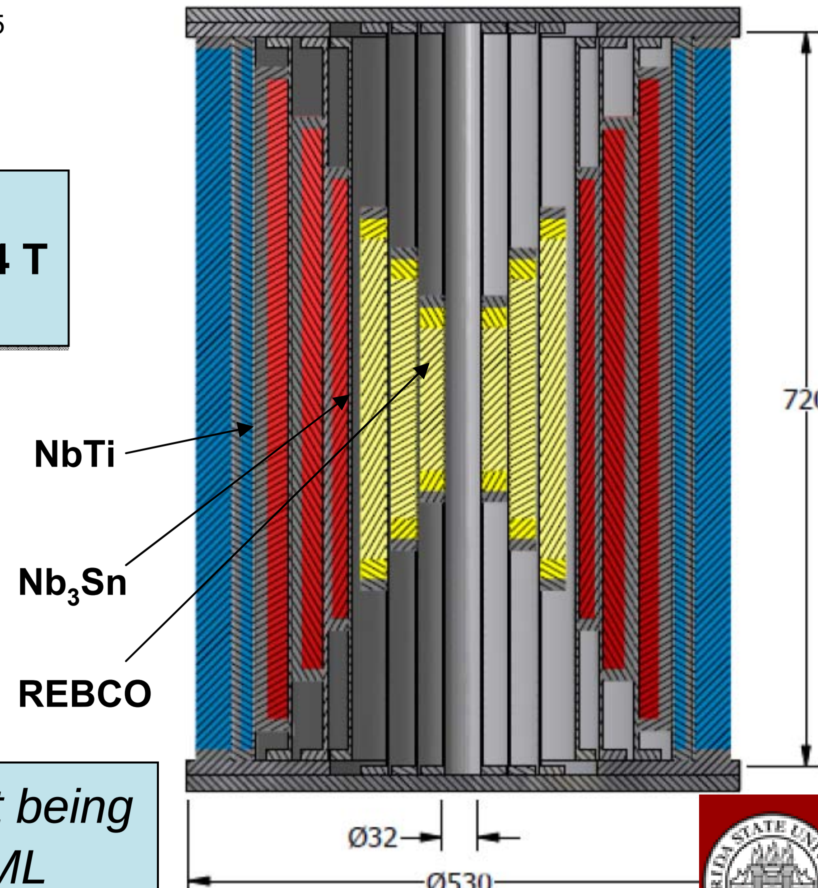
ΔB = 7 T



NHMFL II.
Bmax = 35.4 T
ΔB = 4.2 T



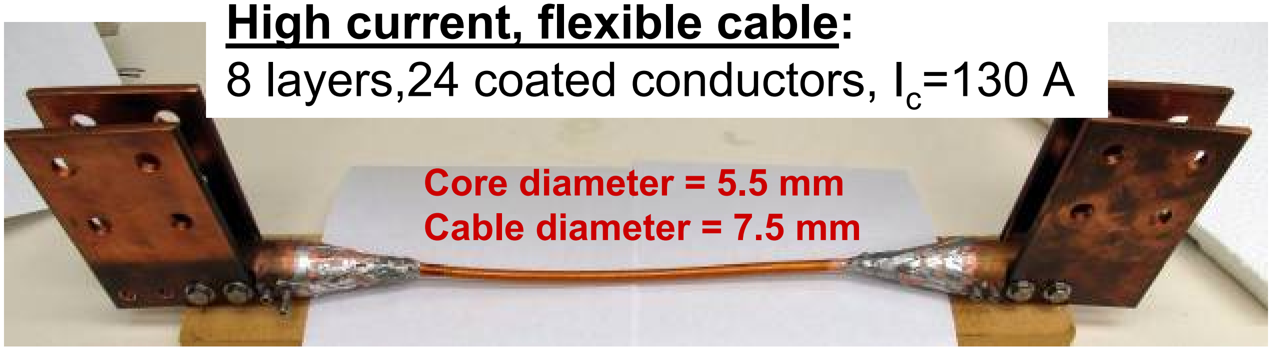


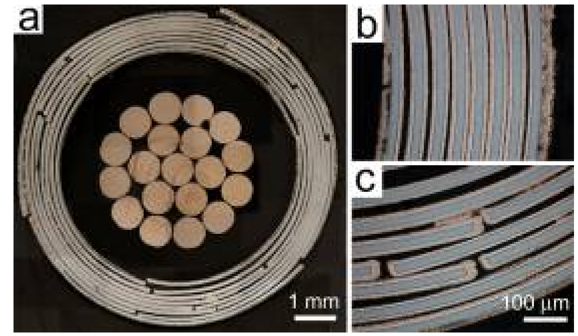


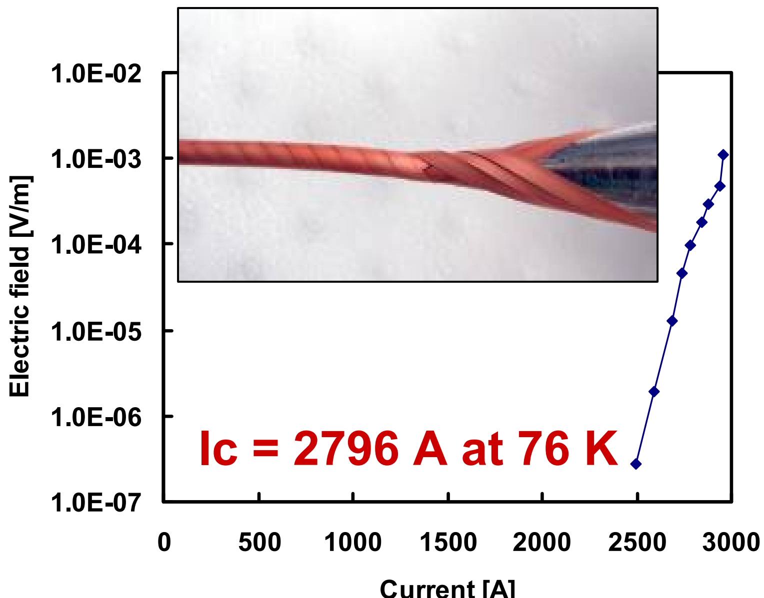
32 T, large bore all superconducting magnet being constructed with coated conductors at NHFML

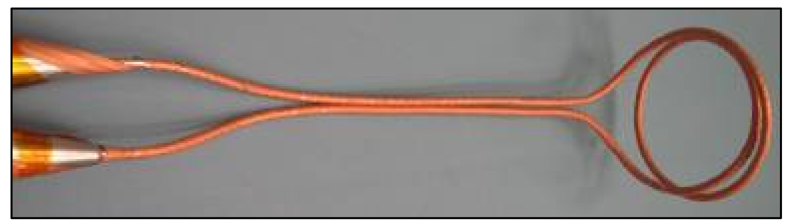
New applications possible with wire's excellent mechanical properties & in-field performance

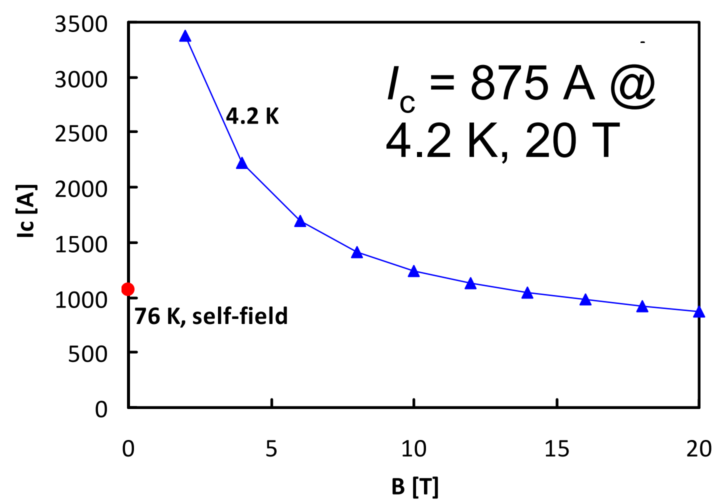
High current, flexible cable:
8 layers,24 coated conductors, I_c=130 A







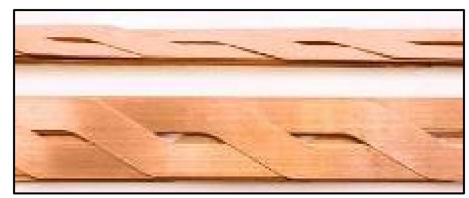




Significant advances in manufacture of coated conductors in the last five years

- Long lengths routinely manufactured
  - 1,000 m demonstrated with minimum Ic of ~ 300 A/cm
  - 100 – 300 m typical shipped lengths
- High critical currents in production wires
  - Critical currents of wires shipped in 2011 range from 80 to 165 A/4 mm with an average of 122 A/4mm

- Excellent in-field performance in high fields at intermediate and low temperatures
  - 800 A/cm (Je = 800 A/mm2) at 4.2 K,10 T, field perpendicular to wire
  - 600 A/cm at 40 K, 3 T, field perpendicular to wire
- Customized to meet unique requirements of multiple applications
  - Excellent 2D uniformity of critical current across width for ROEBEL cables
  - Tight bandwidth of critical current for FCL
  - Several prototypes of cables, FCL, coils demonstrated



- Superior mechanical properties
  - Yield strength >700 MPa with superalloy-based coated conductors

New demonstration projects to advance 2G wire for applications: DOE Smart Grid Demonstration Program

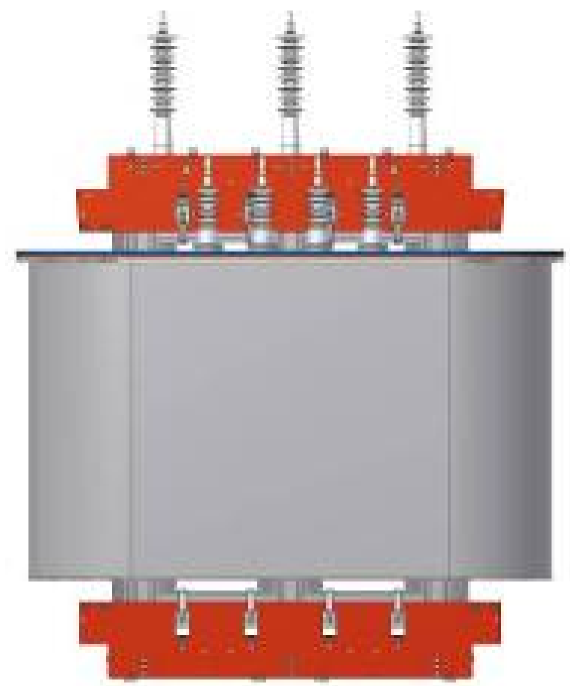
2G Superconducting Fault Current Limiting Transformer

Goal: 28 megavolt-ampere three-phase medium-power transformer with FCL capability

Partners:
Waukesha Electric Systems **–** system design and construction, project lead
SuperPower – wire manufacture
University of Houston – wire improvements
Oak Ridge National Laboratory – cryogenics, high voltage dielectrics
Southern California Edison – host utility

Budget: $21.5 million
Timeframe: 3 years (2010-2013)

Status: new wire configuration under development; device design, FCL modeling, and new wire development underway



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ARPA-E GRIDS Program

Superconducting Magnetic Energy Storage System with Direct Power Electronics Interface

Goal: Demonstration of small-scale prototype (20 kW, 2.5 MJ), leading to UHF magnet storage coil

Partners:

ABB – power electronics, system integration

SuperPower – wire manufacture, coil support

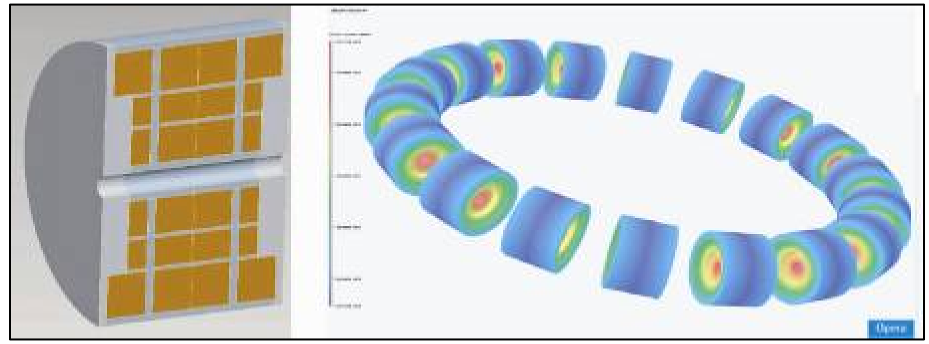
Brookhaven National Laboratory – magnet design, construction, protection and test

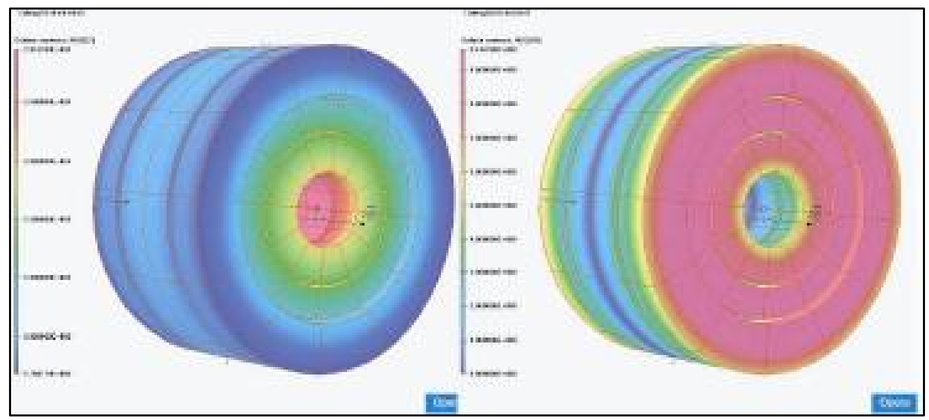
University of Houston – wire process improvements

Budget: $4.2 million

Timeframe: 3 years (2011-2014)

Status: first wire delivered, coil trials begun, MOCVD system modeled, new Ic test system installed, system design work underway





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New Award – October 2011!
ARPA-E REACT Program –

Low-cost superconducting wire for future wind turbine generators

Partners:

University of Houston – project lead, wire improvements

SuperPower – wire manufacture

NREL (National Renewable Energy Laboratory) – impact evaluation of enhanced superconducting wire on overall system performance

Tai Yang Research Company – coil fabrication and test

TECO Westinghouse Motor Company – development of device design

Budget: $3.1 million

Program Period: 3 years

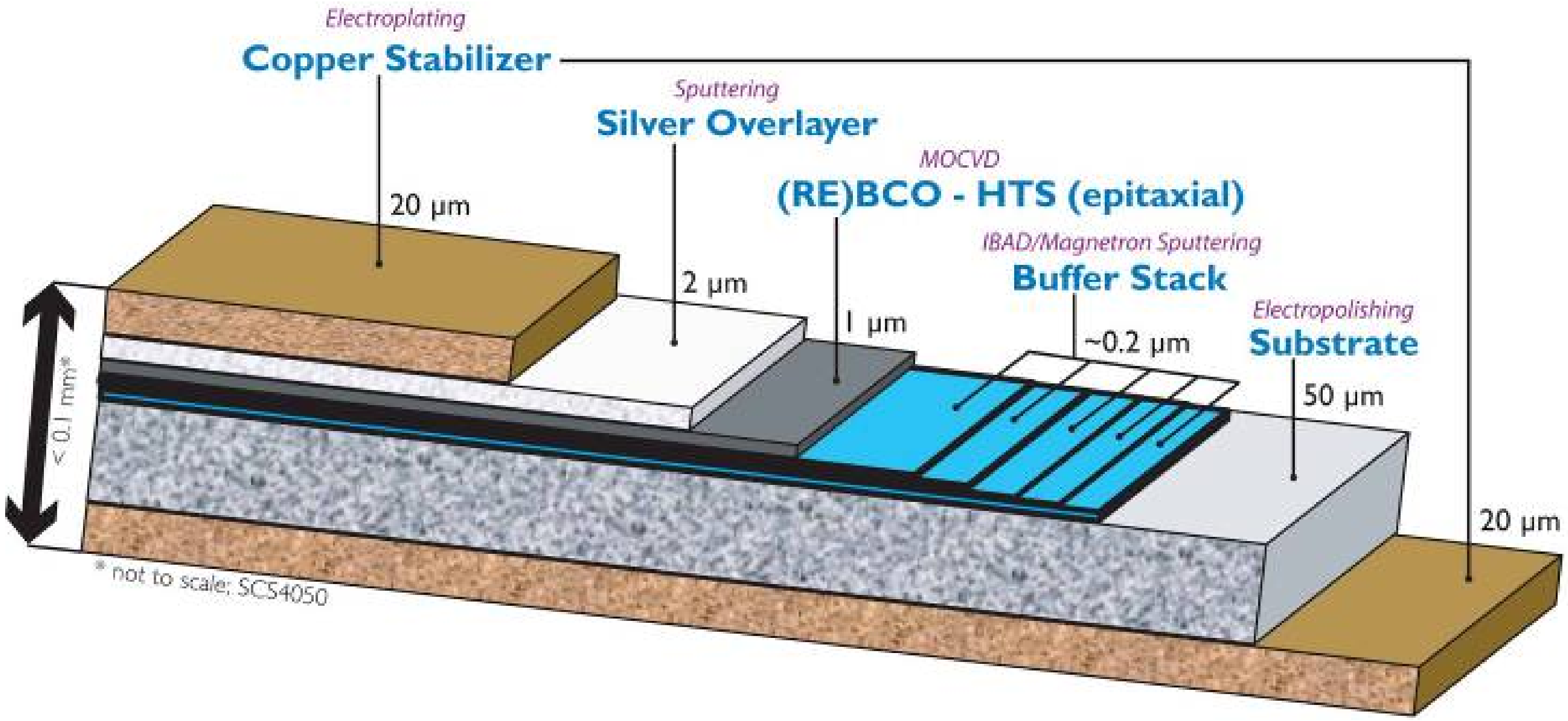
Status: just awarded, contract completion underway

Requirements of 2G HTS wire

- High critical current
- In-field performance
- High mechanical strength
- Long lengths
- High uniformity (along length & across width)
- Low ac loss
- Low joint resistance (<50 nΩ-cm^2 for NMR)

SuperPower® 2G HTS wire architecture

- Hastelloy substrate prepared with electropolishing
- Epitaxial template achieved by IBAD-MgO
- REBCO film deposited by MOCVD
- Sputtered Ag and electroplated surround Cu stabilizer (SCS)



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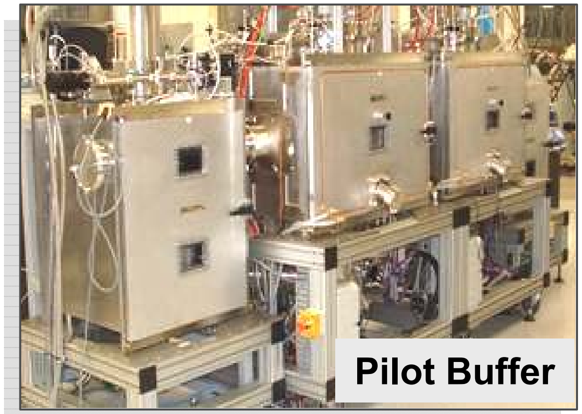
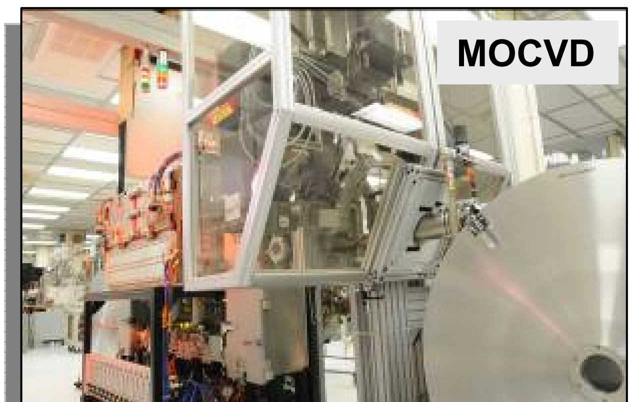
SuperPower manufacturing approach

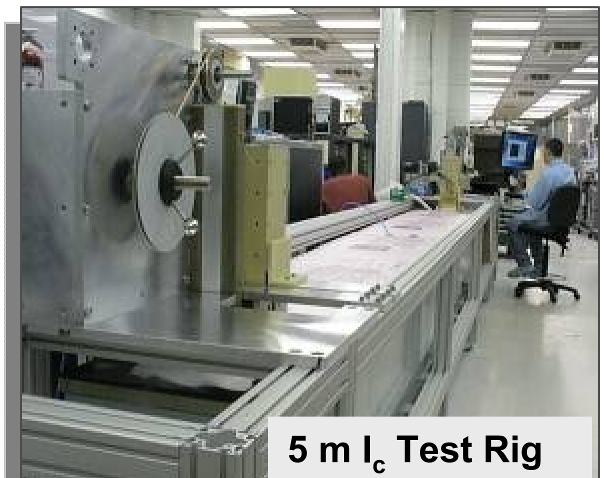

Pilot Substrate Electropolishing


Pilot Buffer


Pilot IBAD


MOCVD


Post HTS


5 m I_c Test Rig

Strong, concentrated emphasis on manufacture of high quality, long length 2G HTS wire to satisfy market demand

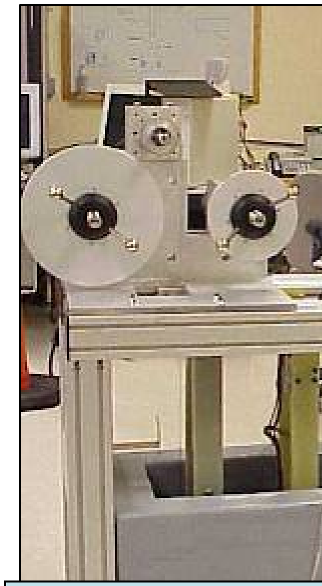
SuperPower's 2G HTS wire production

- Automated reel-to-reel long-length wire mass production
- Various specifications in formulation, performance & dimension
- Real time & integrated quality monitoring and control
- Wire characterization & testing
- Advanced technology research and performance-oriented development

9 Tesla cryostat

Equipment Engineering advances for testing kilometer lengths of coated conductor

- LTS wire is tested only at two ends
- Coated conductor is tested for I_c and n-values **100% over entire length**

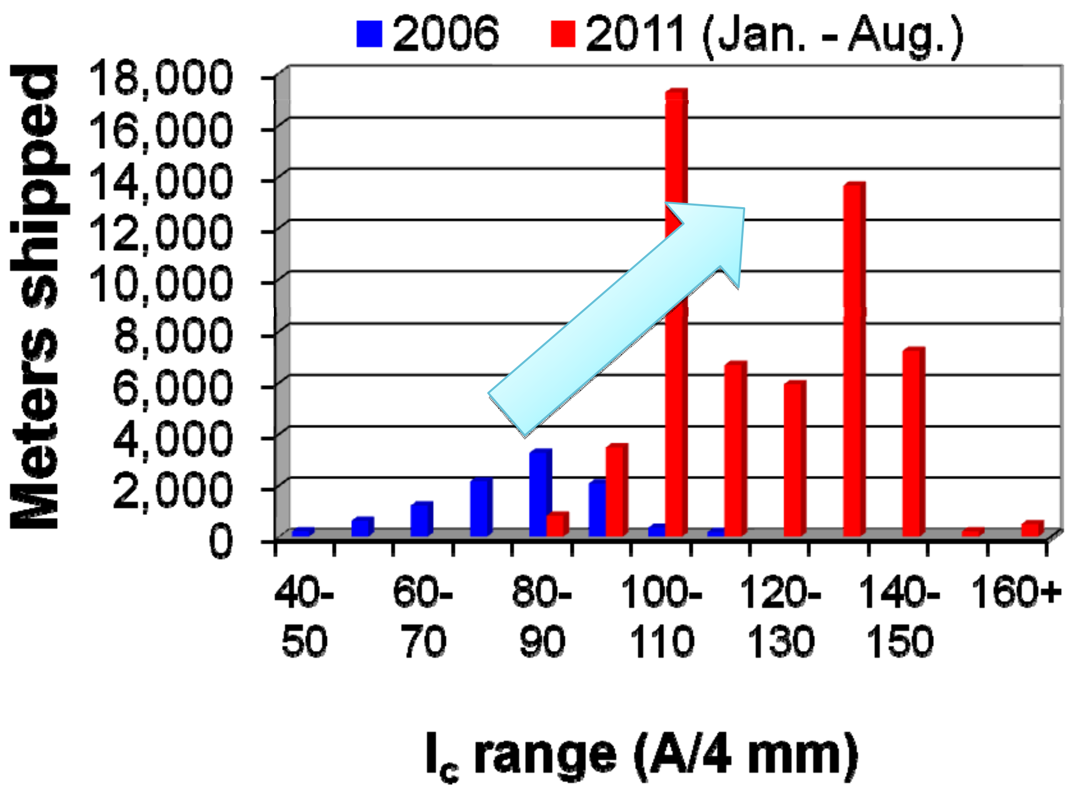


2003: *Ic, n-va*
1 m *intervals*

2006: *Ic, n-value, thickness, width*
measurement in ***5 m*** *interva*

2011: *Ic, n-value, thickness, width*
measurement in ***10 m*** *intervals*

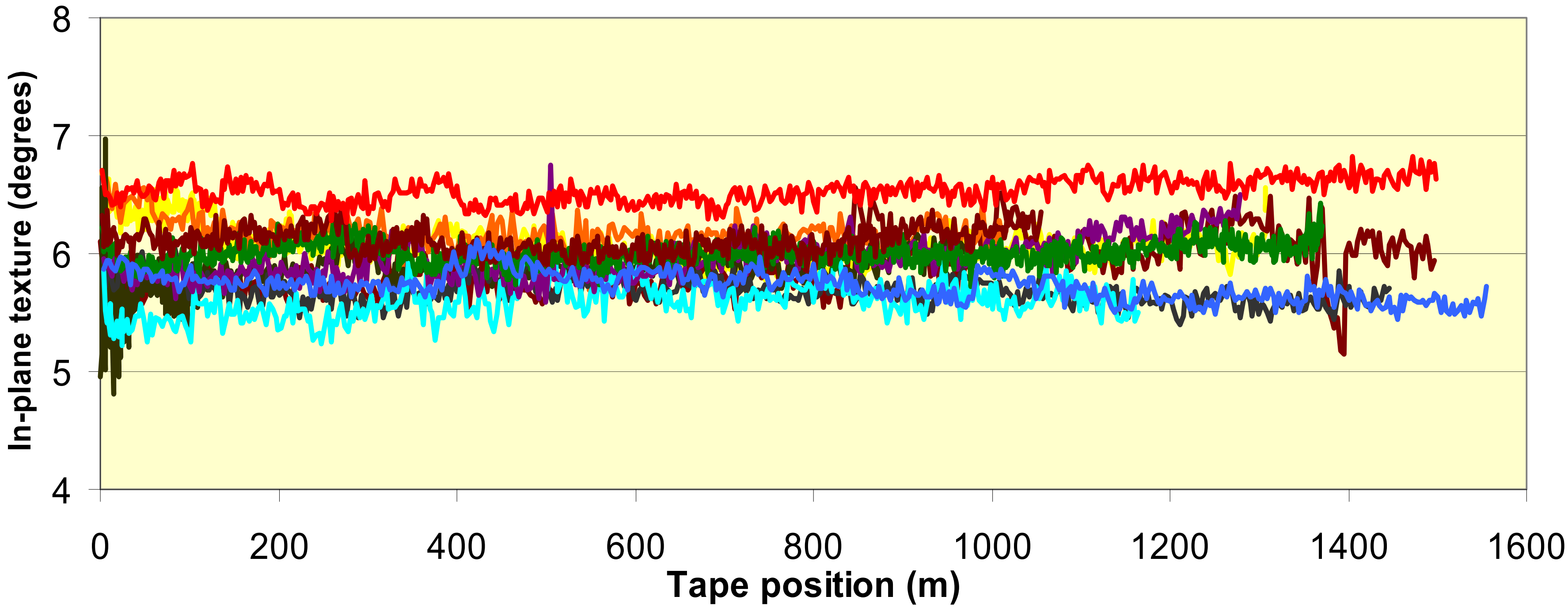
Large increases in coated conductor shipments and performance in last 5 years



Metric	2006	2011
Average I_c (A/4 mm)	80	122
I_c range (A/4 mm)	40 – 118	80 - 165

50% increase in average I_c
100% increase in minimum I_c
40% increase in maximum I_c

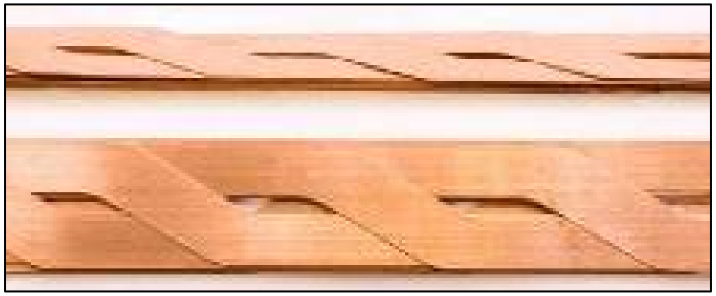
Uniform IBAD buffer stack in long length

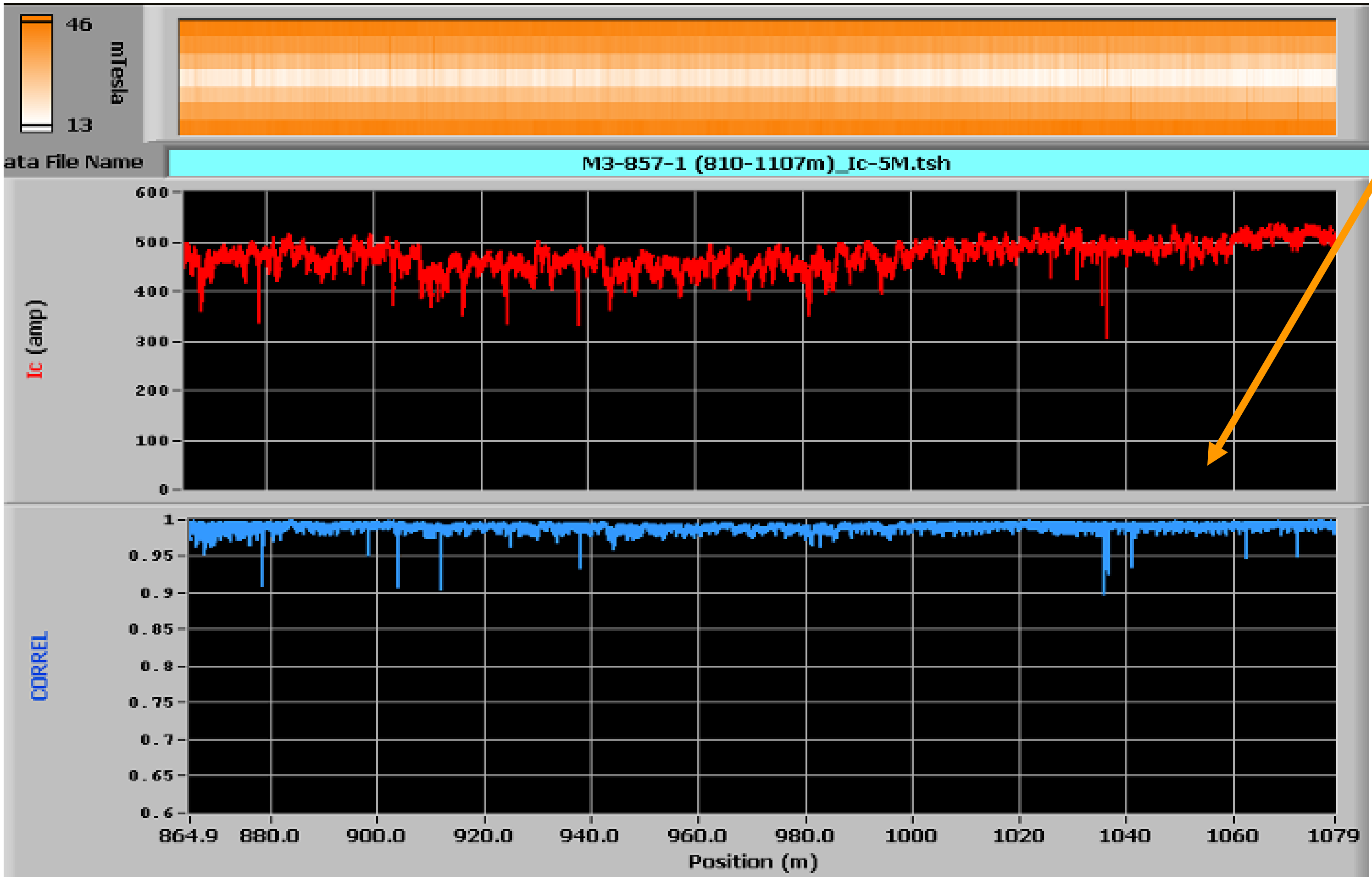


IBAD buffered template in lengths of 1,300 m to 1,500 m with in-plane texture of 5 – 7 degrees and excellent uniformity of ~ 2%

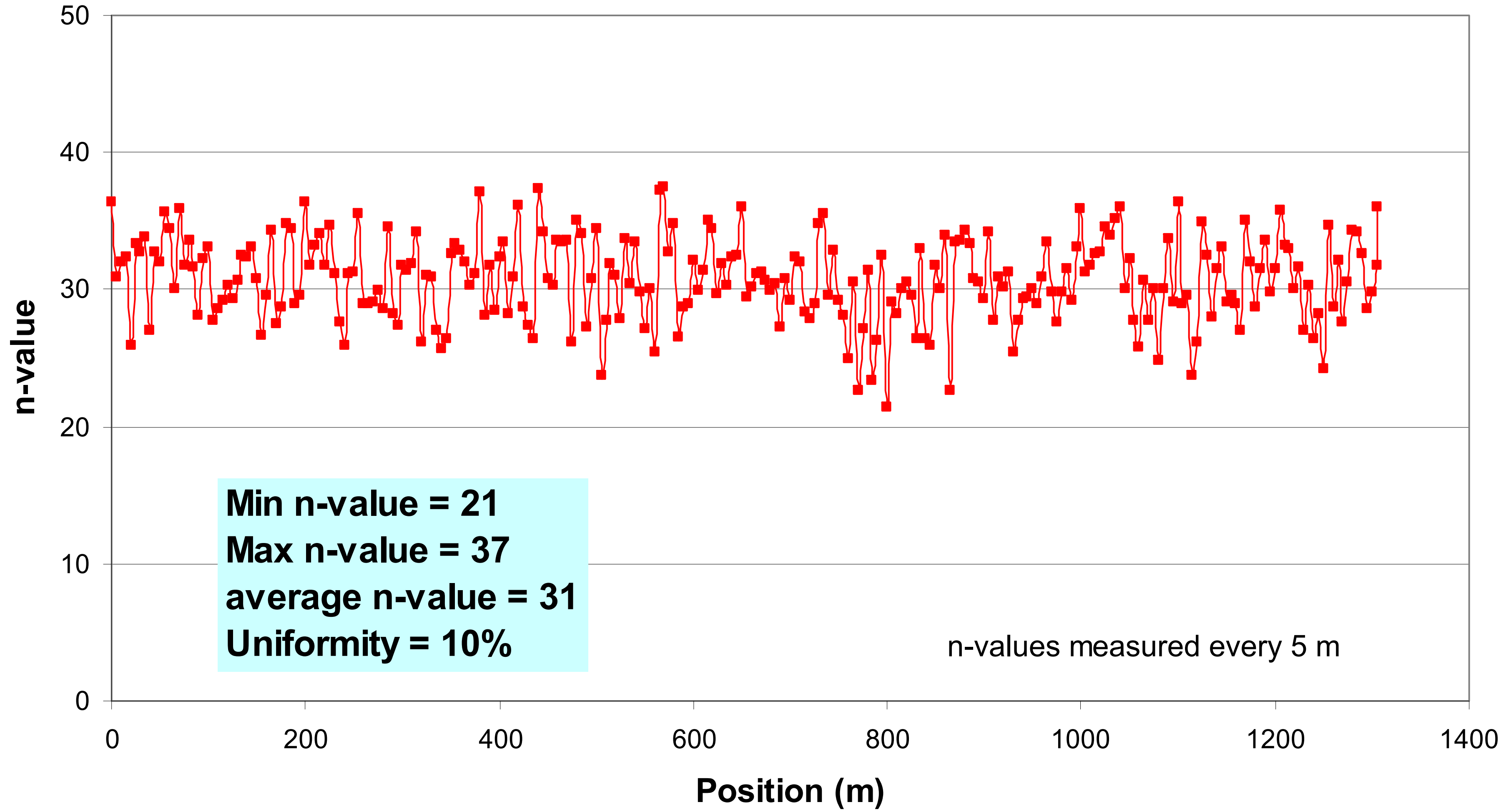
Uniform Ic along length & across width *(2D Uniformity)*

- RSD ≤ 10%, CORREL ≥ 0.9





Uniform n-value in long length



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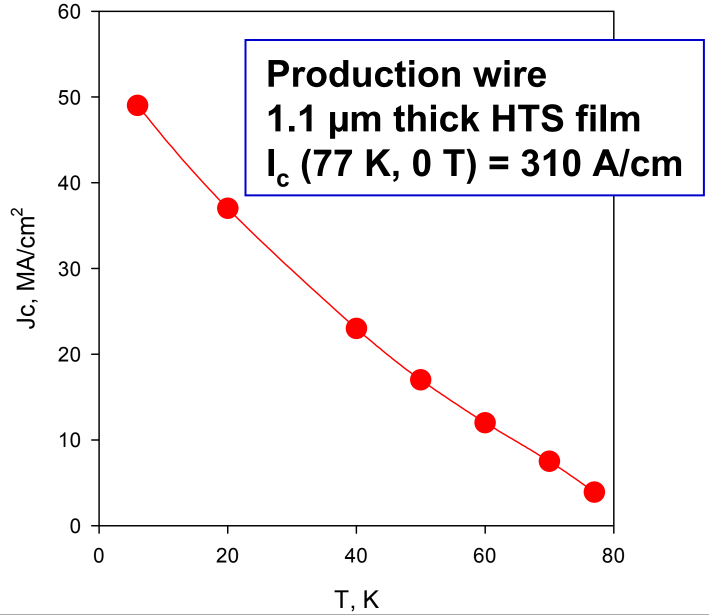
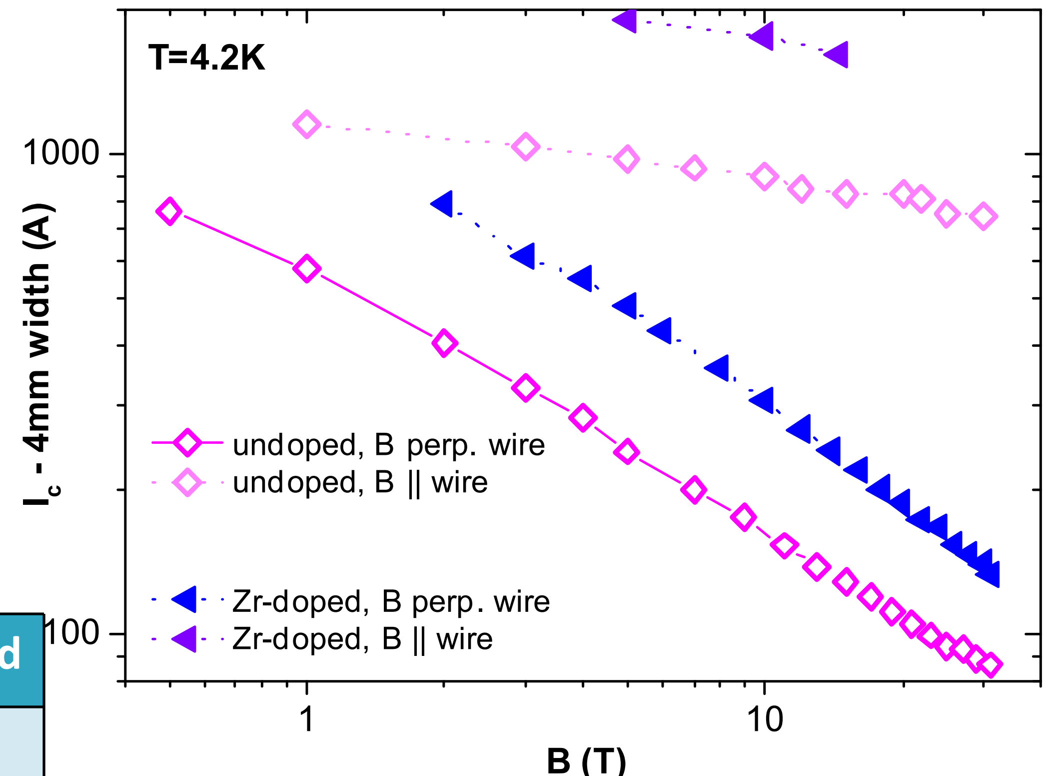
Superior performance in Zr-doped MOCVD production conductors in high fields at 4.2K





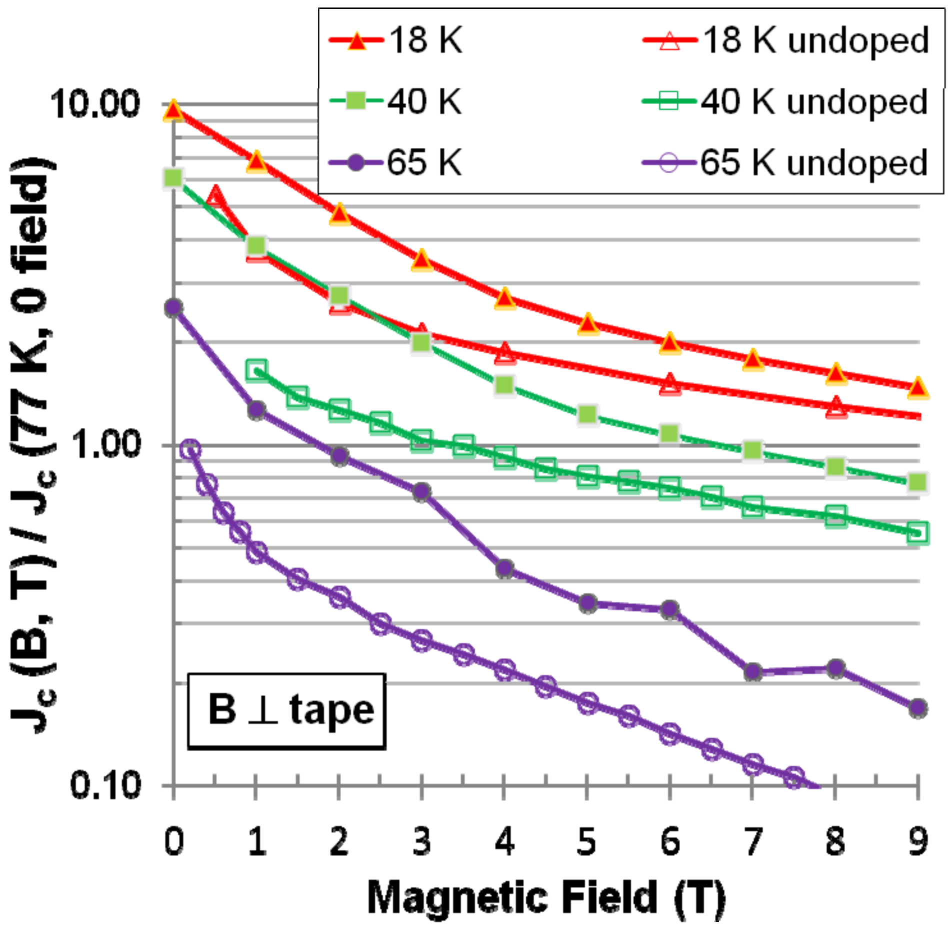
I_c @ 4.2 K (A/4 mm)	Undoped	Zr doped
10 T, B ⊥ wire	163	310
20 T, B ⊥ wire	108	183
5 T, B || wire	971	1,893
10 T, B || wire	899	1,769

Measurements by V. Braccini, J. Jaroszynski, A. Xu,& D. Larbalestier, NHMFL, FSU

In-field performance of Zr-doped production conductors is about two times better than standard conductors in high fields at 4.2 K

National High Magnetic Field Laboratory · FSU · UF · LANL

Improvements in in-field Ic of Zr-doped conductors at intermediate temperatures



Lift Factor of 77K, zero field I_c	65 K 3 T	40 K 3 T	18 K 3 T
Undoped wire	0.27	1.02	2.13
Zr-doped wire	0.73	1.99	3.50
Lift factor of Zr-doped wire is higher by	2.7	1.9	1.6

At 40K 3T, quantity of wire required for device is **reduced by HALF,** greatly improving the economics of the device.

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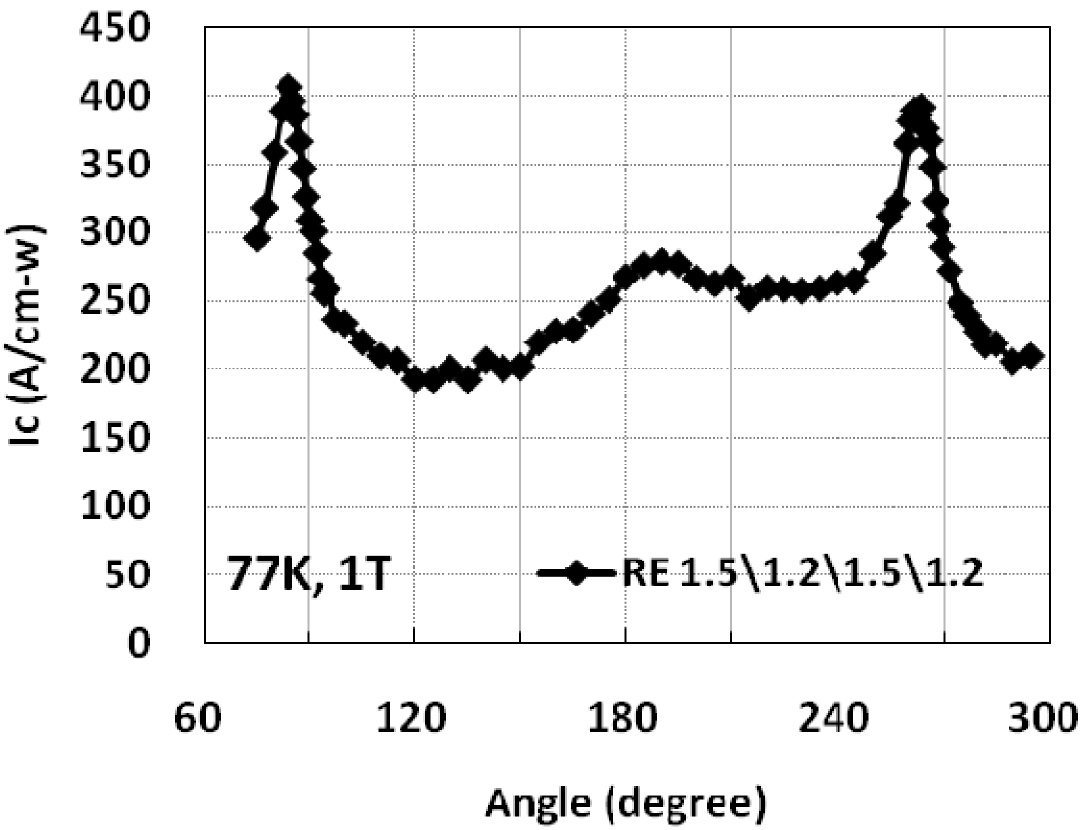
Four passes of Zr:GYBCO with alternating Gd+Y content between 1.5 and 1.2

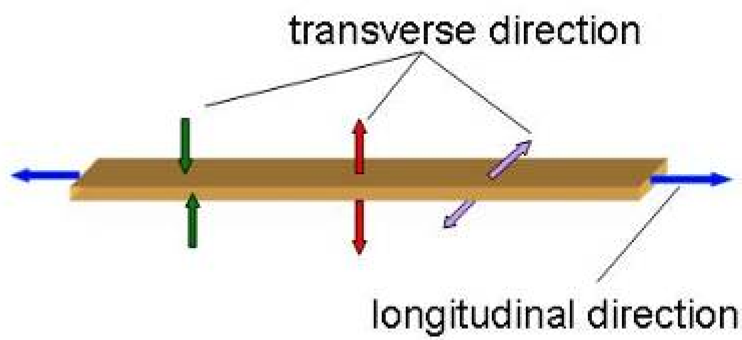


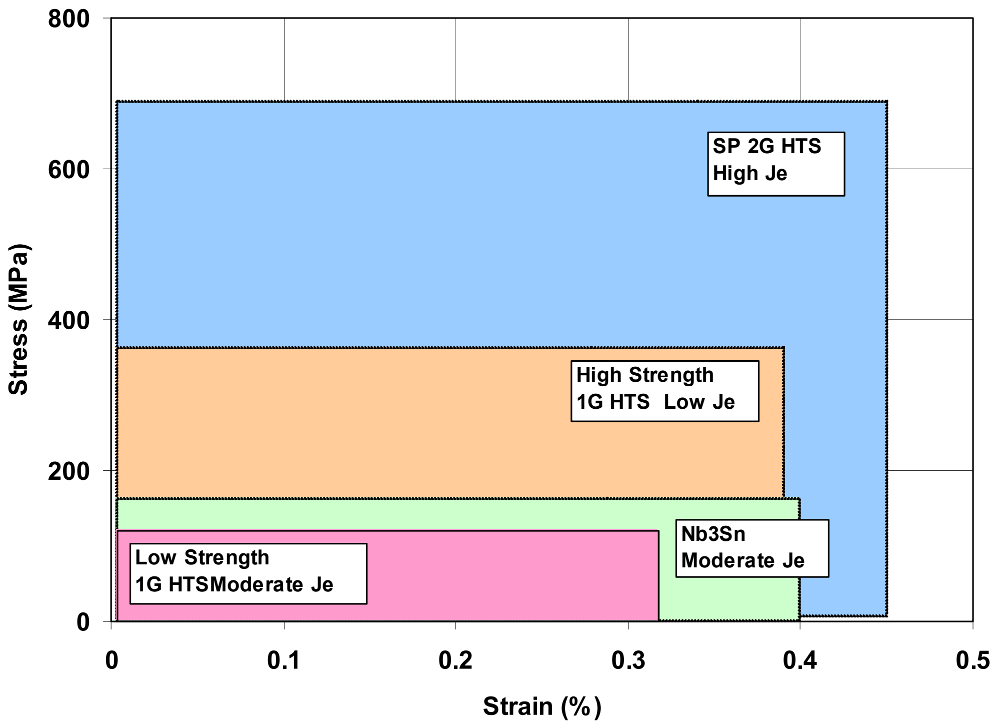
Zr:GdYBCO film made in 4 passes. 0.7μm in each pass.

Gd = Y
Ba =2
Cu = 3.3
Zr = 0.053
Gd + Y = 1.5\1.2\1.5\1.2

$I_{c,min}$(77K,1T) = 194A/cm-w, Ic(77K,0T) = 961A/cm-w, 2.8μm thick

Mechanical property requirements vary with applications



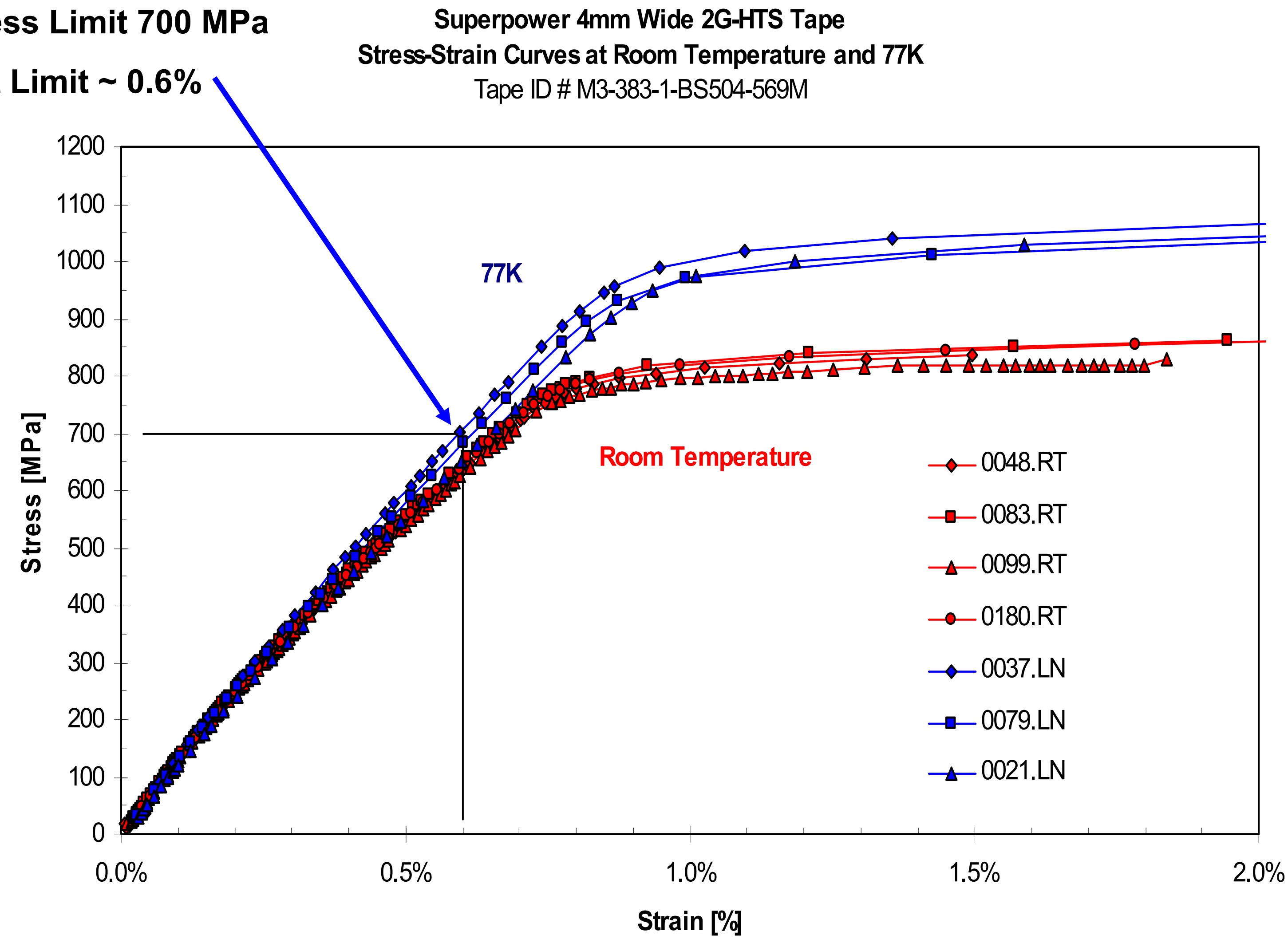


Longitudinal tensile stress and strain limits

Excellent strength in longitudinal direction

77K Stress Limit 700 MPa

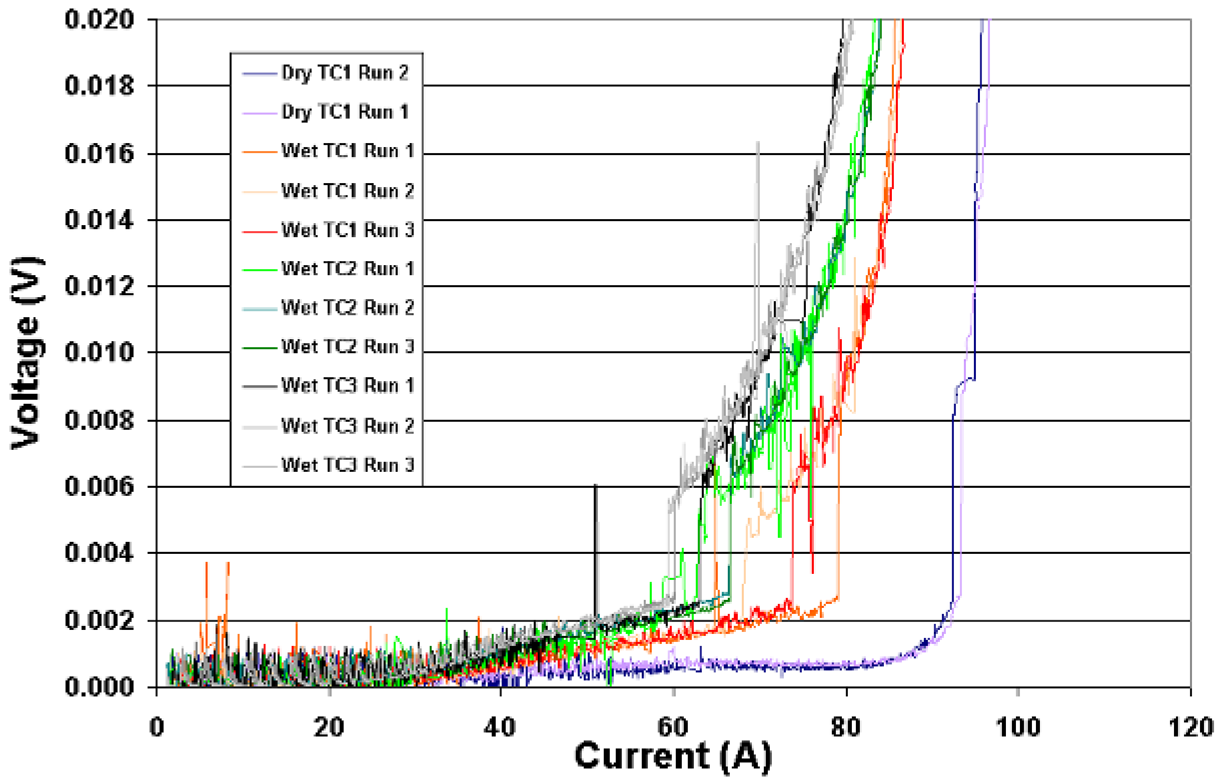
Strain at Limit ~ 0.6%



Data from R. Holtz, NRL

Transversal strength critical to coil performance

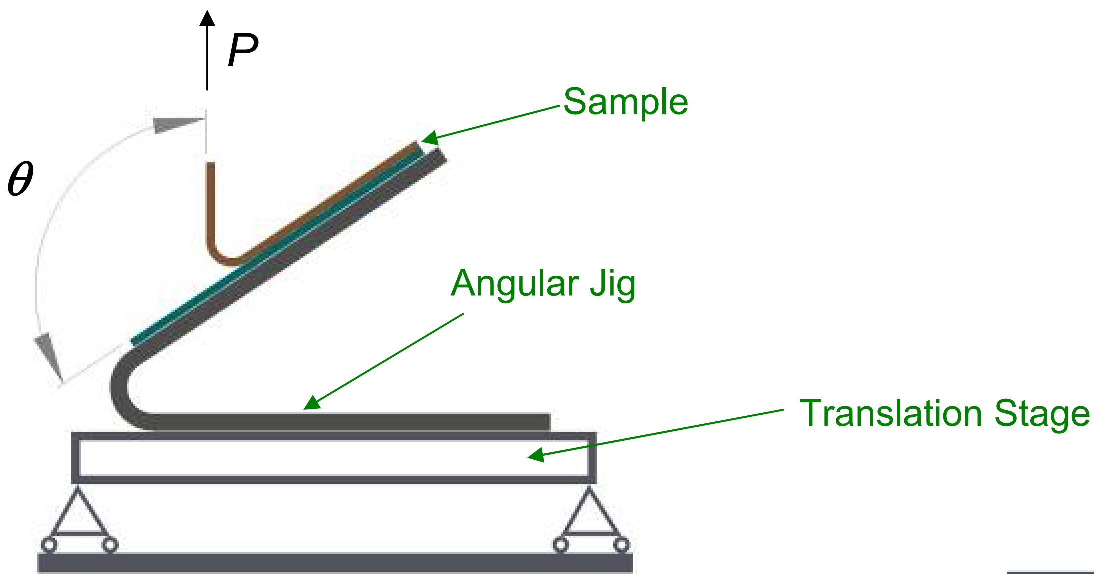
- Coil I_c drops through thermal cycling between RT and 77K
- Degradation occurs only to epoxy wound or impregnated coils
- Believed to be due to transverse tensile stress originated from difference in coefficients of thermal expansion

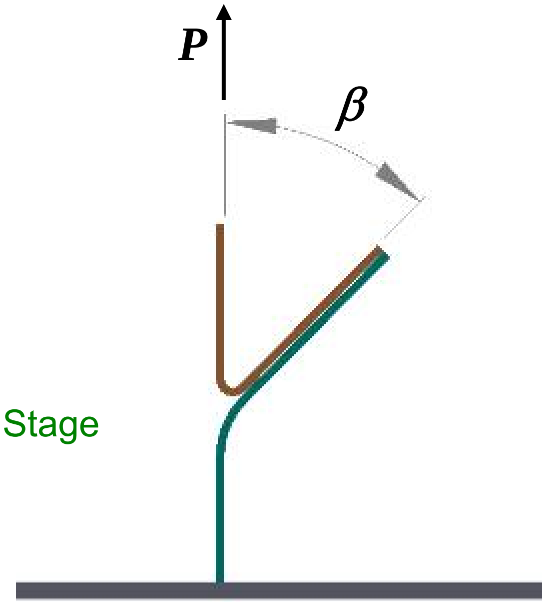


I-V curves of dry- & wet-wound coils

Understand and resolve the issue by failure analysis, stress modeling, wire testing, wire strengthening and coil winding technique improvements

Peel test – measurement of adhesion strength

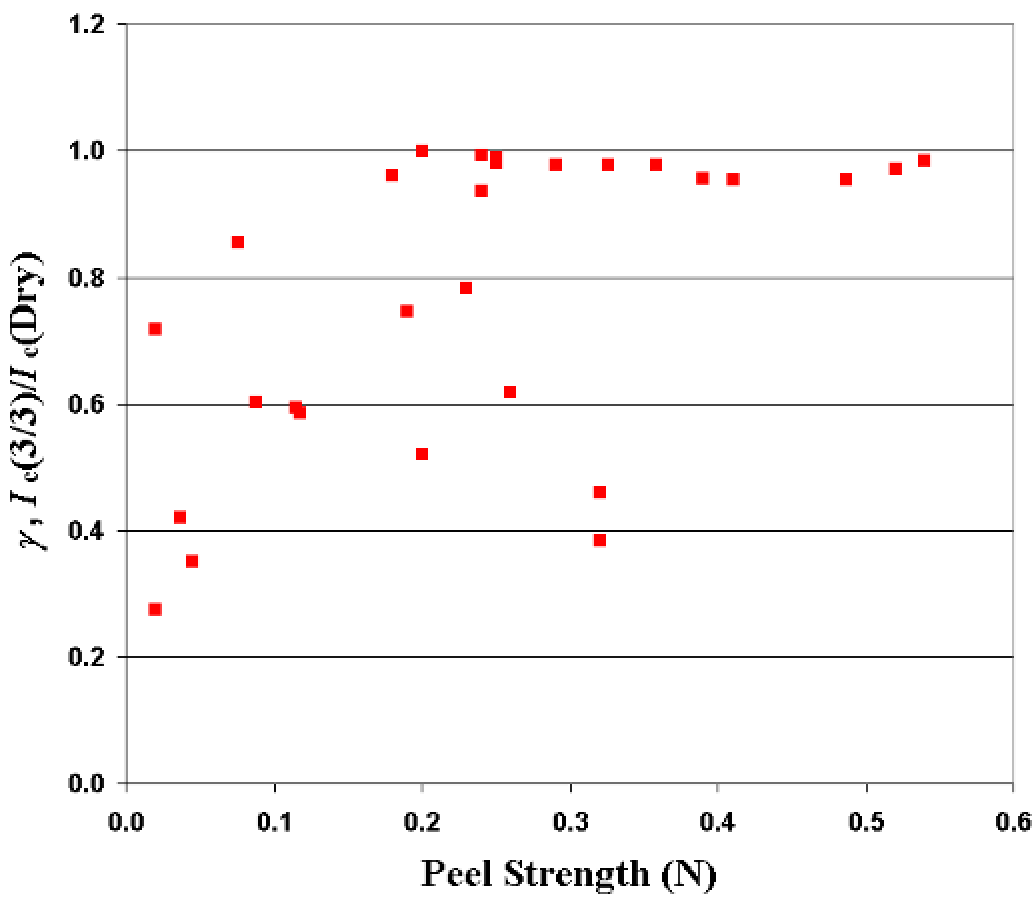




Fixed peeling angle peel test

T-peel test

Correlation between coil performance and peel strength



$$\gamma = \frac{I_c(3/3)}{I_c(dry)}$$

I_c(3/3) – critical current from the 3rd measurement at the 3rd thermal cycle from the wet-wound coil

I_c(dry) - critical current from the 1st measurement at the 1st thermal cycle for the dry-wound coil

Performance of wet-wound coils is dependent on wire's peel strength

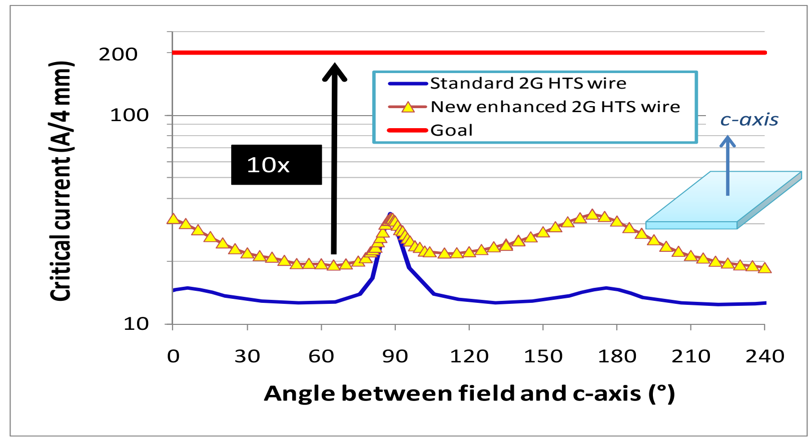
Summary of technology development goals

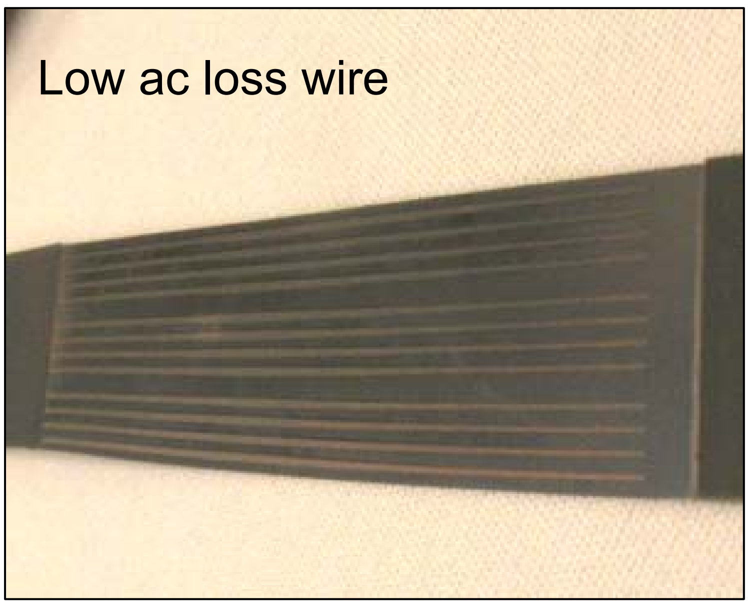
Achieve higher amperage

	Today	2 yrs	5 yrs
Ic at 77 K *	100-130 A	200 A	300 A

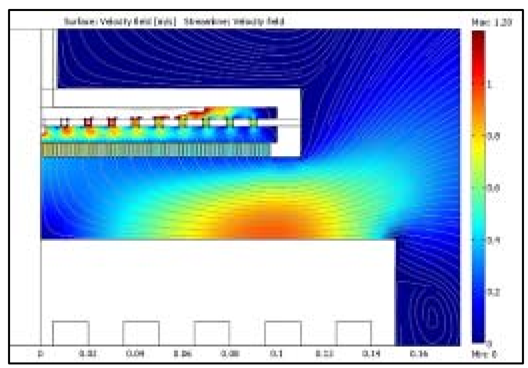
* 4 mm width

Improved in-field performance





Increased production and reduced cost



New MOCVD Reactor Design

Silver electrodeposition

SuperPower driving Price / Performance down on two fronts: Improving manufacturing process and in-field performance

Time	Performance at 77 K, zero field	Lift Factor at device operating condition	Performance at device operating condition	Wire price ($/m)	Wire price ($/kA-m) at device operating condition
Now	100-130 A	2	260 A	$ 45	$175
2 years	160 A	4	640 A	$ 35	$ 55
4 years	200 A	6	1200 A	$ 35	$ 30

Improving wire performance is key to success

* Based 4mm width

Summary

- REBCO-based 2G HTS wire is entering a large market, as various devices are being developed for practical power applications
- SuperPower is continuously upgrading its manufacturing capacity & efficiency, and improving its wire performance & quality
- R&D efforts are focused on
  - o Increased Ic levels
  - o Further enhancement in flux pinning for better in-field performance
  - o Lower AC loss through filamentization
  - o Higher mechanical strength for improving reliability
  - o Simplified structure and processes for lower cost

Thank you for your attention

- For more information, please visit

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  or info@superpower-inc.com